Journal of Cleaner Production 182 (2018) 485–495

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Informal collection, recycling and export of valuable waste as transcendent factor in the municipal solid waste management: A Latin-American reality

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ARTICLE INFO

Article history:
Received 6 October 2017
Received in revised form
5 February 2018
Accepted 6 February 2018
Available online 12 February 2018

Keywords:
Municipal solid waste management
Life cycle assessment
Socio-economic impact
Recycling
Informal collection
Waste exportation

ABSTRACT

The informal collection, storage, and commercialization of Valuable Solid Waste (VSW) performed by waste pickers is a complex and dynamic socioeconomic phenomenon. In developing countries, the waste pickers play a major role as suppliers to companies dedicated to the commercialization of VSW, thus contributing to mitigate the environmental impact of the municipal solid waste management (MSWM) systems. This research work presents the logistic and geographical structure of the informal collection, commercialization, and national and international recycling of VSW recovered from a medium size city in Mexico. The life cycle assessment methodology is used to determine the environmental impact that recycling VSW from informal collection has on the MSWM system. The functional unit is defined as the management of one ton of municipal solid waste. The functional unit displays a climate change index of 1090 kg CO_2 eq, while the recycled VSW has the potential to mitigate it by −116.5 kg CO_2 eq. The marginalization index is a way to assess the socioeconomic condition of the waste pickers. This index shows that the waste pickers suffer high marginalization, despite the fact that they contribute with 72% of the total collection of VSW.

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1. Introduction

Municipal solid waste management (MSWM) is a complex problem that mainly affects underdeveloped and developing countries. The Mexican government has established models for MSWM as part of its legislation, where actions aimed at reducing the disposal of MSW in sanitary landfills (SL) are considered. These include actions such as waste production minimization, waste classification at the source, reuse and recycling of valuable solid waste (VSW), as well as material and energy valorization of the waste (SEMARNAT, 2008).

Between 2000 and 2010, the generation of MSW in Mexico grew 30.26%, compared to a 15.17% population increase for the same period. This resulted in a generation of 40.1 million tons of MSW in 2010. During this period, the gross national product grew 33.1%, while the waste generation *per capita* went from 0.83 to 0.93 kg/day (SEMARNAT, 2012). MSW generation displays a complex relationship with the economic development and population dynamic of a

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https://doi.org/10.1016/j.jclepro.2018.02.065
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society (Chen et al., 2010).

According to SEMARNAT, in 2012, 72% of Mexico's MSW was disposed in SL and other regulated sites, 23% was taken to open landfills, and the remaining waste was recycled. In the same year, there were 260 SL in operation that fulfilled the required regulations (SEMARNAT, 2012).

In the last years, the collection, storage and recycling of VSW has been encouraged, since it went from 2.3% in the year 2000 to 5% in 2012 (Góngora-Pérez, 2014). Although, this is still far behind compared to other countries: the world's average is 19% (Gutberlet, 2015), 25.3% in the European Union (da Cruz et al., 2014), and 8–10% in China (Chen et al., 2010).

The collection, storage, commercialization, and recycling of VSW in Mexico have increased due to the price and demand hike of polyethylene terephthalate (PET), paper, cardboard, and metal scraps. Since 2015, Mexico has become the main recycler of PET in Latin-America, since it salvages 50.4%, equivalent to 722,000 t, of PET present in the MSW. From these, 40% were shipped to China and the rest were reprocessed in Mexico in 15 different facilities, with a total processing capacity of 300,000 t/year (ECOCE, 2017). In the year 2012, 3.2 million tons of paper and cardboard were recovered, 1.6 million tons were imported, and only 177,000 tons were sold to China (CNICP, 2012).

The MSWM systems in developing countries are generally inefficient since they lack the proper administrative and financial structures, good regulations, infrastructure, and adequate human resources. The informal collection of VSW done by waste pickers is a partial solution to these problems, despite the fact that this activity has a negative social perception (Navarrete-Hernandez and Navarrete-Hernández, 2018). Approximately, 1% of world's urban population is involved in the recovery of VSW; in Latin America, Asia, and Africa, the work of these people accounts for nearly 30% of the VSW recovery process (Gutberlet, 2015).

The different forms in which the recovery of VSW are done by the waste pickers and their importance have been studied mainly in Brazil (Tirado-Soto and Zamberlan, 2013), and in Asian countries (Asim et al., 2012). Brazil is taking steps toward the recognition and formalization of the waste pickers activities, through urban cooperatives or unions, and public regulation (Gutberlet, 2015). The creation of waste pickers' cooperatives has the potential of improving their conditions by allowing them to demand their rights, improve the collection of VSW, and negotiate a better sales price for the collected VSW. Additionally, it provides an opportunity to educate the waste pickers on how to handle hazardous waste, such as electric and electronic devices (Ghisolfi et al., 2017). Thus, knowledge of their daily income, living and working conditions, and the hierarchical structures among the waste pickers groups, are required to improve their social inclusion and work formalization (Sasaki et al., 2014).

In Mexico, the recovery of VSW is fundamental for the recycling companies, and for the national and international trade market of products such as PET, paper, aluminum, and other materials. Nevertheless, official information on this activity is scarce. A study done in 2008 about informal collectors that worked in 15 SL found that their socioeconomic condition has improved compared to the one from the 1990's. A 71% of the waste pickers owned a house build with bricks and concrete, 52% have attended middle school and 23% elementary school, and infant work has declined. Regardless of these improvements, the waste pickers are still a marginalized sector of society (Niño and Hernández, 2012). This marginalization is associated to a lack of social opportunities, and skills needed to acquire or generate such opportunities, as well as privation and lack of accessibility to basic goods and services required for well-being (Almejo-Hernández et al., 2013). The social impacts are a consequence of the positive or negative pressure from the surroundings on the well-being of the different participants in the various stages of a process. Currently, the social impact can be evaluated with a focus on life cycle assessment (LCA) (UNEP, 2009). In this work, we use the measured marginalization as a social impact indicator.

In order to achieve sustainability in modern societies, the recycling of MSW is essential. Thus, MSWM systems must be directed to strengthening the markets and the recycling industries (Exposito and Velasco, 2018). Nevertheless, as it has been mentioned, the collection and availability of VSW as input to the recycling industries in the developing countries, depends to a great extent on the work done by the waste pickers. In many countries, this activity has not been characterized, nor its relevance on the sustainability of the urban areas has been systematically evaluated. A more in-depth knowledge of this activity is essential to regulate, legislate, and above all improve the quality of life and the social inclusion of the waste pickers. The objective of this work, is to characterize and evaluate the structure of the informal collection, storage and commercialization of VSW in the City of Celaya, in central Mexico, using the LCA methodology. With the aim of objectively estimate the contribution of the recycling industries in the environmental impact reduction of the MSWM system. Additionally, the socioeconomic condition of the waste pickers as a social group is evaluated through a marginalization index. This information is useful and fundamental to generate public laws and programs to dignify the work of the waste pickers.

2. Material and methods

This research work follows the LCA methodology. Sections 2.1 and 2.2 explain the objective and breath of the research, Section 2.3 expands on the analysis for the life cycle inventory, and Section 2.4 covers the evaluation of the social and environmental impacts.

2.1. Socioeconomic description of the city of Celaya

The City of Celaya is part of Celaya's county, in the state of Guanajuato, and is located in the north central region of Mexico, Table 1 shows some features of the City of Celaya. The main economic activities are divided between the service industry (66%), the secondary sector (26%), and the primary sector (8%). The secondary sector has been growing continuously due to the investments in several industries, such as agro-industry, food, metal working, and more recently automobile production (Cobarrubias-Valdenebro, 2014). The county has an estimated economic growth between 3.9 and 4.2%

2.2. Description of the municipal solid waste management system

The information needed for this work was put together from different sources, namely the Government of Celaya (2012–2015)

Table 1
Main characteristics of the City of Celaya.

Feature	Amount
Geographic location	Latitude: 20° 31′24″ N Longitude: 101° 48′ 55″ W
Total area	553.18 km^2
Total population	468,469 inh
Urban population	72.66%
Rural population	27.34%
Economic activities	
Service industry	66%
Secondary sector	26%
Primary sector	8%

through the General Municipal Services' office, the Municipal Institute of Ecology, and from the collection, storage, commercialization, and recycling companies involved in the process. Waste pickers that collect VSW from the streets and from the SL were also surveyed. The system describing the MSWM in the City of Celaya is shown in Fig. 1, all the mass flows were estimated for the year 2015.

2.2.1. MSW collection process

The municipal system and authorized companies are in charge of collecting the MSW. The waste is manually collected at fixed points from the sidewalks. The recovery of VSW is complex and carried out informally. Several pathways for VSW's recovery are identified in Fig. 1 (Recovery I-VI). Recovery I is an initiative from the local government to classify and recover VSW directly from government and academic institutions. Recovery III and IV consider the classification and recovery done directly by the municipal and private operators during the waste collection, respectively. Recovery V covers the classification and recovery of a small fraction of the waste, done directly in a facility at the final disposal site. The waste pickers are the major players in classifying and recovering VSW in the inside of the SL's cells (Recovery VI), and directly on the streets (Recovery II), although this is informal. The amounts and types of waste in each Recovery process (I-VI) were obtained through a survey made to the waste pickers, which is included as supplementary material.

The City of Celaya has more than 160 privately owned VSW sites that buy, store, process and sell the VSW recovered. These sites are classified in two types: minor and major sites (Fig. 1). The minor sites classify and sell the VSW in bulk. While the major sites have the infrastructure needed to classify, process, and package the VSW in bales that are usually taken to regional storage sites for their sale. Most of the VSW recovered in the city are sold outside of the county and only a fraction of the companies that recycle PET do manufacture pellets by mixing recycled PET with virgin PET resin.

2.2.2. MSW disposition (landfill)

The City of Celaya has a SL composed of three confinement cells. The cells are identified as CEMIR I, II, and, III, respectively. They are designed and operated according to the norm NOM-083-SEMARNAT-2003. The cell CEMIR III was in operation during the year 2015, with a daily intake of 300–350 t, and during 2016 this increased to 400 t/day. The cells are equipped with a biogas collecting system, unfortunately the collected biogas is released directly into the atmosphere. There are more open landfills in the county, but they are illegal since they operate in abandoned lots, by the highways or next to dirt roads hidden in the countryside.

2.2.3. System definition and functional unit

The products of the MSWM system are shown in Fig. 1 with their respective processes and mass flows. Each block represents an operating module, the arrows represent the mass flows. The grey frame represents the city's MSWM system border, before the VSW are sent to the storage and recycling centers. The VSW are sold as raw material to different local, national, and international industries. These recycled wastes represent environmental credits, since they substitute products of the same kind and quality.

The functional unit (FU) considered is one ton of MSW disposed from the urban areas, shown as an orange arrow in Fig. 1, its composition is available in Table 3. For the purpose of the LCA, inside the borders of our system, the resources needed for the collection and processing of the MSW are considered, such as fossil fuels and electricity from the national electric grid, among others.

2.3. Inventory of supplies consumption and anthropogenic pollution

2.3.1. Inventory of supplies consumption

The consumption of different fossil fuels, electricity, water, and other resources used in the Recovery V block and the SL were obtained directly from the 2014–2015 Operative Budget provided by the county administration (2012–2015). The fuel consumption of the block Recovery IV was provided by the local collection companies. As for the others Recovery blocks, no fuel consumption is considered, since they consist mainly of manual labor and the transport of waste to the minor storage sites is done in non-motorized vehicles. Additionally, the classification done inside the minor storage sites is also performed manually.

The resources associated with the major storage sites are the fossil fuels needed for the collection and shipping of VSW acquired from the minor storage sites, the classification facility, and the SL. These were estimated based on the routes used by the trucks to ship the VSW from the different sites to the major storage sites, by geographically locating the different sites, as shown in Fig. 3.

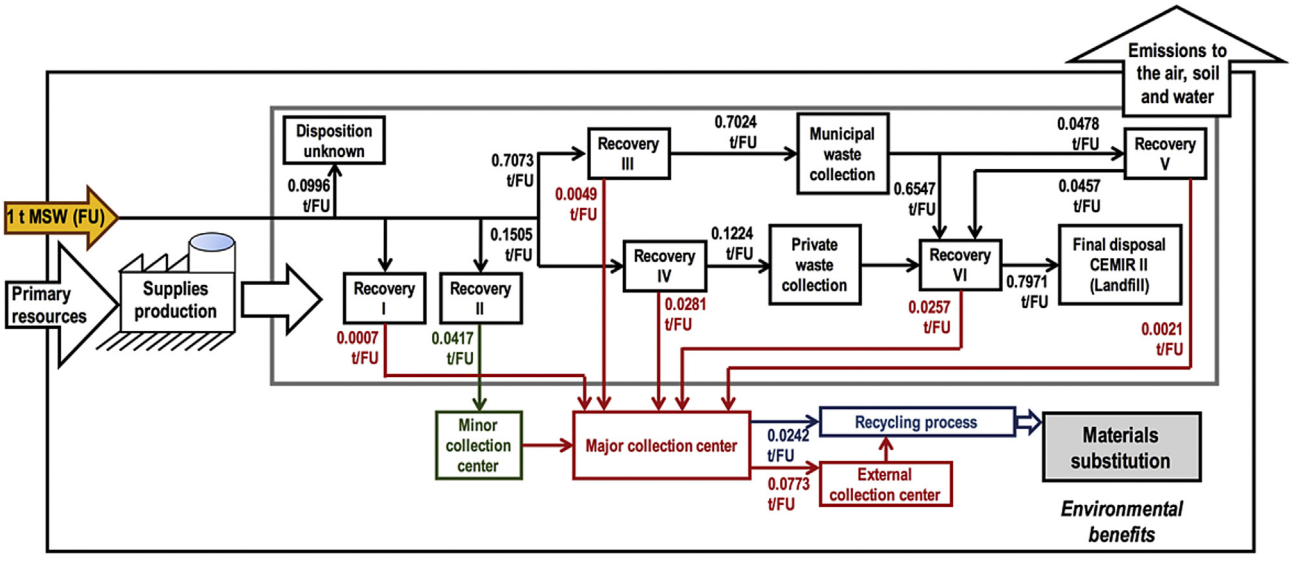

Fig. 1. Municipal solid waste management system for the area under study. FU: functional unit, 1 t of municipal solid waste (MSW).

Some of the materials recovered by the MSWM system are eventually subjected to recycling processes (Table 2). These processes are modeled using a closed loop system via the substitution method. This method assumes that the recycled materials can be used to manufacture the same original product, with the same quality. Thus, it presupposes that the recycled material and the raw material share the same characteristics (ISO-14044, 2006).

The main considerations of the recycling processes, and the efficiency relating the amount of material recovered *vs.* waste processed are shown in Table 2. The emissions and raw materials needed in the different recycling processes in Table 2 come from the Ecoinvent 3.1 data base (Ecoinvent-Center, 2014). There are other materials besides VSW that are also recovered, such as fabrics (0.12 kg/FU) and rubber (1.63 kg/FU). There is an increased use of rubber as an alternative fuel in the cement industry, since it has an energy content of 23.03 MJ/kg (Chatziaras et al., 2016). Cement companies in Mexico use rubber as a substitute of petroleum coke in their clinker furnaces (Andellac, 2017); but due to the fact that the percentage of rubber in the MSW composition is very low, its recovery and recycling was not taken into consideration.

2.3.2. Inventory of anthropogenic pollution

The emissions generated by the vehicles used for shipping waste were estimated using GREET (GREET, 2016). The SL's biogas production was calculated using the version 2.0 of the Mexican Model for Biogas (MMB) (SCS-Engineers, 2009). The emissions of C-CO_2 from the SL are not considered as an environmental impact, due to their biogenic origin (IPCC, 2006).

The lixiviates generated by the SL are contained in an open lagoon with a capacity of approximately 2000 m^3. Few research works report the amount of lixiviates generated based on the MSW stored in a confinement cell of the SL, the values reported exhibit a large dispersion in L lixiviates/t MSW: 440 (Fernández-Nava et al., 2014), 125 (Yusof et al., 2009), Zafar and Alappat (2004) reported an average of 440 for two active landfills in a period between June and September in India, and 310.4 of which 112.5 L were due to rain (Rieradevall et al., 1997). These variations can be attributed to several causes, such as rainfall, (Lin and Li, 2009), water content and composition of the MSW, and the operation of the SL.

This work considers the environmental impacts of the SL for 50 years, as this is the estimated time for the production of biogas to cease according to the simulations based on the MMB and the findings reported by Aldana-Espitia et al. (2017). During the same period the total amount of lixiviates generated is estimated to be 2000 L/t MSW (Koroneos and Nanaki, 2012). Due to the fact that lixiviates generated inside the SL extract organic matter from the waste, a change in its average composition through time is considered, an initial composition for the first 20 years, and a second composition for the remaining years (a similar approach is considered by Koroneos and Nanaki, 2012). The composition of ammoniacal nitrogen in lixiviates was evaluated using the characterizations by Yusof et al. (2009).

The lixiviates in the lagoon represent an environmental impact since they are not subjected to any treatment. The gas emissions are based on the IPCC's guide for the national inventory for greenhouse gases (IPCC, 2006), and the guide for the inventory for emissions of air pollutants (EMEP/EEA, 2013).

The resources needed and pollution generated that is associated with the manufacturing of the equipment and the construction of the facilities used in the MSWM system were not considered in this analysis, in agreement with Chi et al. (2015). In the other hand, the resources needed for the operation of the MSWM system are considered inside the frontiers of our system (Fig. 1). The life cycle inventories for these resources were obtained from the Ecoinvent 3.1 data base (Ecoinvent-Center, 2014).

2.4. Impact evaluation of the environmental and social life cycle

The LCA evaluation model of the MSWM was done using the software SimaPro 7.3.3 PhD® (PReConsultants, Amersfoort, the Netherlands). The Life Cycle Impact Assessment (LCIA) was based on the ReCiPe 2008 method (Goedkoop et al., 2009), using two levels for the indicators of the harmonized categories, namely midpoint and endpoint.

The socioeconomic condition of the waste pickers was evaluated through a marginalization index (MI). The MI is a statistical parameter that helps identify the social groups in a country that lack the opportunities for their development, and the capacity to find or generate such opportunities (CONAPO, 2010). The socioeconomic dimensions used to estimate the MI in this work include: education, housing, and access to general goods, along with eight forms of exclusion. The forms of exclusion cover the conditions and deficiencies generally expressed as percentage of population, as presented in Table 6. The MI is normally estimated for a specific location; in this work, it was calculated for a specific demographic group: the waste pickers. This estimation is based on the forms of exclusion data that were collected via direct survey of the waste pickers. The average values of each form of exclusion are then weighted to conform the MI. The final numeric value of the MI can be categorized as very low, low, medium, high and very high. These categories are obtained via clustering analysis (Almejo-Hernández et al., 2013). The methodology and index were used by the Mexican Population Council during the 2010 national census.

The survey used to determine the MI exclusion factors was answered by a sample of 36 waste pickers, out of a total population of 1075 individuals. Thus, the data has a 90% trust interval according to the procedure outlined in Walpole et al. (1998). The survey was applied all through the city, making sure to cover all the quadrants on the urban area. It is worth mentioning, that most of the subjects refused to answer the survey. Besides the questions asked to assess the exclusion forms, the subjects were asked to provide other information such as age, birthplace, previous work, hours per day dedicated to waste picking, daily income, if they have been the target of any kind of discrimination, access to healthcare, if

Table 2
Recycling processes characteristics.

Recycled material	Amount recycled (kg/FU)	Material replaced by recycled material.	Efficiency	Reference
PET	38.66	PET granulates from virgin material	61%	Soares (2010); 3-Drivers (2012)
Paper, paperboard and waxed cardboard	47.87	87% * of virgin sulfur pulp	86% **	* Eriksson et al. (2005); * CNICP (2012) ** Ferreira et al. (2014)
Aluminum	2.46	Primary aluminum	96%	EEA (2013)
Ferrous materials	4.99	Pig iron	84%	Ferreira et al. (2014); EC et al. (2007)
Glass	2.10	Glass from virgin materials	88%	Ferreira et al. (2014)
HDPE	5.37	HDPE granulates from virgin material	83%	Arena et al. (2003)

PET: Polyethylene terephthalate. HDPE: High Density Polyethylene. FU: Functional Unit.

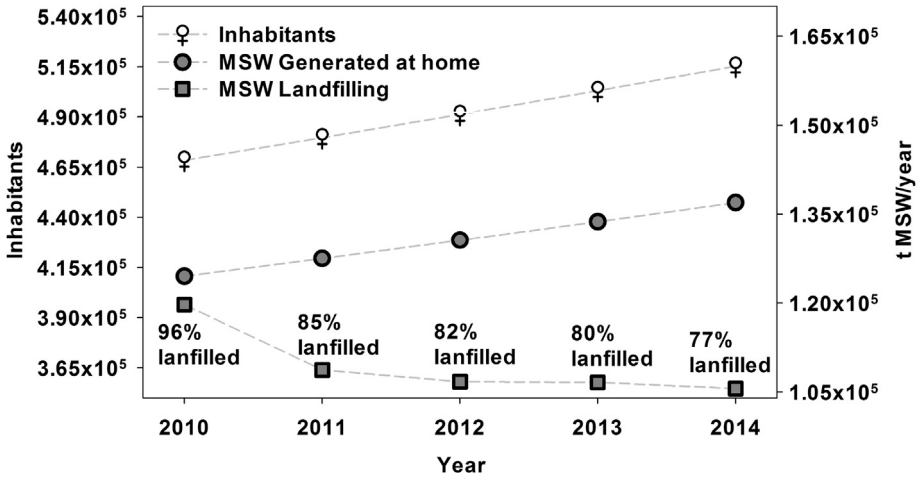

Fig. 2. Population growth, municipal solid waste generated, and confined in a sanitary landfill.

they suffer any illness related to their activities as waste pickers, and the type and amount of VSW that they collect in each stage of the process, Recovery I – IV. The survey can be found in the supplementary material.

3. Results and discussion

3.1. System and inventory characterization

The estimated population growth in the City of Celaya between the years 2010 and 2014 is seen in Fig. 2. The 2015 census showed that the city had 494,304 inhabitants. Additionally, the estimated generation of MSW, considering a *per capita* production of 0.728 kg/day is observed in Fig. 2, alongside the amount of waste confined in the SL. The decrease of MSW sent to the SL is associated with an increase in the VSW recovery. During the year 2015, approximately 105,565 t were sent to the SL, with a daily input between 265 and 322 t/day. It is estimated, that nearly 31,400 t of VSW were recovered.

According to our survey, each waste picker that works on the streets (Recovery II) collects an average of 41.30 kg VSW/day (3.71–252.86 kg/day). Approximately 180 informal waste pickers work in the SL, according to the SL's administration, each one recovering up to 66 kg VSW/day. Almost 0.40% of Celaya's population, 1975 people, work in the collection and recovery of VSW.

Waste composition according to its stage of generation, collection, storage, recycling, and confinement in the SL is presented in Table 3. It can be observed that food and yard waste comprised the main part of the waste at its source of generation, since this type of waste is not subjected to any kind of recycling or special treatment. On the other hand, plastics, paper, paperboard, aluminum, and other ferrous materials have the highest rate of recovery. Mexico is the leading country in PET recovery in Latin America. This activity has grown considerably in the last few years: 8.16 Gg of this material were recovered in 2002, 119.2 Gg in 2007, 400 Gg in 2012, and 422.8 Gg in 2016 (ECOCE, 2017). Despite the fact that plastic, paper, and paperboard waste have a high percentage of recovery, aluminum is almost completely recovered, with a 96%. The national

Table 3
Approximate composition by type of waste generated, recovered, confined, and recycled.

Type of waste	Generation 1000 kg/FU	R-I 0.7 kg/FU	R-II 41.7 kg/FU	R-III, IV 33 kg/FU	R-V 2.1 kg/FU	R-VI 25.7 kg/FU	Minor collection 41.7 kg/FU	Mayor collection 103.2 kg/FU	ECC 77.3 kg/FU	Recycling 103.2 kg/FU	Landfill 797.1 kg/FU
	(%)										
Food	33.94										38.38
Yard waste	25.36										28.68
Wood	1.48										1.67
Cotton	0.20										0.23
Cloth	0.34					0.46		0.11	0.15		0.37
Synthetic fibers	0.13										0.14
Leather	0.14										0.16
Diapers	5.44										6.15
PET	8.01	50.00	21.47	60.00	15.03	36.79	20.95	37.28	18.30	38.1	4.18
Hard plastics	0.77		4.67	5.00	7.06	6.60	4.56	5.22	6.80	5.3	0.19
Rubber	0.48		3.27		1.03	1.02	3.19	1.58	2.06		0.33
Paperboard	8.17		58.73	20.00	28.18	24.69	57.32	36.53	47.59	37.1	4.45
Paper	6.60	50.00	5.17	10.00	7.36	17.03	5.05	9.89	12.88	10.0	6.17
Waxed cardboard	1.05		0.22				0.21	0.09	0.12	0.1	1.17
Aluminum	0.26		5.66		0.70	0.44	5.52	2.39	3.12	2.4	0.02
Ferrous materials	0.76		3.27	4.01	3.54	8.94	3.19	4.85	6.32	4.9	0.23
Clear glass	2.41			0.50	25.67	4.03		1.66	2.16	1.7	2.51
Colored glass	1.00			0.50	11.43			0.39	0.50	0.4	1.08
Construction waste	2.53										2.86
Slab and ceramic	0.21										0.24
Other inorganic	0.74										0.84

ECC: External Collection Center. PET: Polyethylene terephthalate.

Table 4
Valuable solid waste contributions by recovery stage.

Type of waste	Generation	Recuperation	Recuperation	R-I	R-II	R-III, R-IV	R-V	R-VI	Formal	Informal
	kg/FU	kg/FU	%	% Of recovery by type					%	%
Cloth	3.40	0.12	3.53					100.00		100.00
PET	80.10	39.00	48.69	0.84	23.11	51.00	0.81	24.24	52.65	47.35
Hard plastics	7.70	5.40	70.13		35.89	30.34	2.71	31.06	33.05	66.95
Rubber	4.80	1.63	33.96		82.86		1.30	15.84	1.30	98.70
Paperboard	81.70	37.20	45.53		64.51	17.35	1.55	16.60	18.90	81.10
Paper	66.00	10.03	15.20	3.18	20.98	32.05	1.49	42.29	36.73	63.27
Waxed cardboard	10.50	0.10	0.95		100.00					100.00
Aluminum	2.60	2.50	96.15		94.89		0.59	4.53	0.59	99.41
Ferrous materials	7.60	4.99	65.66		27.06	26.21	1.46	45.26	27.67	72.33
Clear glass	24.10	1.75	7.26			9.53	30.95	59.51	40.49	59.51
Colored glass	10.00	0.39	3.90			40.89	59.11		100.00	
Total	298.50	103.2	34.58							

average for aluminum recovery is close to 97%. While glass has a fairly low recovery percentage due to its low selling price, the inherent risks associated with handling it, and its weight.

The contribution of each type of VSW recovery stage is presented in Table 4. The informal recovery, represented by Recovery II and IV, stand out from the rest. Recovery II is done directly on the streets, while Recovery IV is performed inside the SL. The VSW generated represent 29.85% of the MSW, but its rate of recovery is only 10.32% of the MSW. The informal collection accounts for 71.69% of the total VSW recovered. Some waste pickers in Recovery II can collect up to 253 kg/day; they accomplish this by buying the VSW directly from the business and residential areas that generate them, at a low price. In this way, the generation, collection, and recovery of selected wastes are done in a single step. By doing this, the waste pickers are able to recover high quality VSW, since they anticipate the municipal (Recovery III) and private (Recovery-IV) waste collection.

There are several local and regional organizations in Mexico that organize groups of waste collectors, waste pickers, and waste storers. These informal organizations under the rule of petty leaders are known as “waste collection networks”. Three of these organizations dedicated to the collection, storage and sale of VSW operate in the City of Celaya.

The urban area within the county, and the location of 99 storage centers, of which only 22 are formal, are shown in Fig. 3. Most of the storage centers are located on the outskirts of the city. The major storage sites are strategically located to receive the VSW from the minor storage sites, the SL, the classification plant, trash collectors, and waste pickers. The average distance between the minor storage sites and its closest major storage site is 3.7 km. The VSW are moved

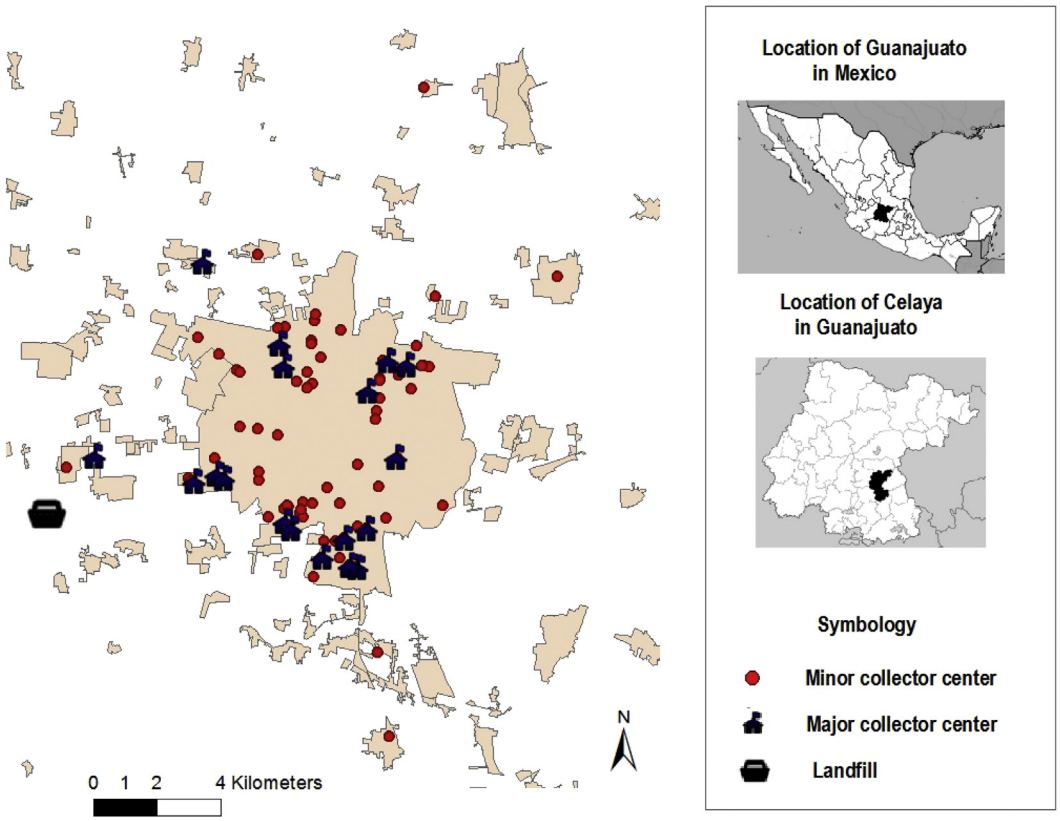

Fig. 3. Distribution of the minor and major storage centers in the urban area of the City of Celaya, Guanajuato, MX.

Table 5
Use of resources and energy in all the stages of the MSWM system.

Stage	Gasoline (L/FU)	Diesel (L/FU)	Gas LP (kg/FU)	Electricity (kWh/FU)	Water m^3/FU
Recovery I					
Recovery II					
Recovery III		0.053			
Recovery IV	0.130	0.170	0.015		
Recovery V	1.70E-03			0.049	4.50E-05
Recovery VI		1.80E-03			
Municipal waste collection	0.540	7.300			1.50E-04
Private waste collection	0.580		0.063		
Final disposal (CEMIR II)		0.990			0.02
Minor collection center					
Mayor collection center	0.990			1.900	
External collection center		0.140			

between the storage sites using pickup trucks, with an average load of 0.75 t and a fuel consumption of 4.5 km/L. The storage sites form a structure that supports the recovery, appraisal, and recycling of a considerable portion of the MSW.

The formal and informal participants in the waste management make use of resources in their daily operation, mainly fossil fuels, electricity, and water. The amount of resources needed in each of the stages of the MSWM is presented in Table 5. The main consumption of fossil fuels comes from the collection stages. The classification and recovery of VSW stages don't use fossil fuels or other resources, since they are comprised of manual labor, with no physical of chemical transformation involved that can have an environmental impact.

3.2. Environmental impacts of the current scenario

The FU is taken as the basis for the calculation of the environmental impacts and consumption of resources. The emissions of greenhouse gases (GHG) by the MSWM system are estimated to be 1090 kg CO_2 eq; this result is similar to those presented in a couple of studies found in the literature, which make similar LCA and MSWM systems' considerations: Eriksson et al. (2005) reported a value of 938 kg CO_2 eq/t MS and Mendes et al. (2004) 920 kg CO_2 eq/t MSW. The methane in the biogas, released by the SL, accounts for 1176 kg CO_2 eq. The recycling of VSW represents savings of 116.5 kg de CO_2 eq, 189.75 m^3 of water, and 58.98 kg Oil eq. The collection and classification of waste don't have a heavy environmental impact, with only 30.5 kg CO_2 eq. These results are in agreement with those reported by Aldana-Espitia et al. (2017), since they found that the SL and recycling of VSW are the components with a major impact in the MSWM system.

Single score indicators for the different stages of the MSWM system, based on the environmental impact categories of ReCiPe's endpoint, are shown in Fig. 4. The stages for Recycling and Sanitary Landfill have the biggest impact with respect to the other stages, with −17.55 y 40.89 Pt, respectively. The critical factor identified in Fig. 4 is the climate change effect on human health indicator, which is caused by the GHG emissions of the SL. The mitigation of the environmental impacts of recycling is due to the substitution of materials and fossil fuels needed in the processing of raw materials. The guidelines proposed on this analysis are to capture and use the biogas from the SL, and to foster the classification and recycling of VSW. These guidelines are in agreement with the government's policies established in the year 2008 (SEMARNAT, 2008), unfortunately these aren't followed properly (SNIARN, 2017).

The recovery and recycling stages were previously considered as a single stage (Bovea and Powell, 2006). It can be observed in Fig. 4, that the impact of recovery can in fact be absorbed by the recycling stage without any loss to the analysis' results. Nonetheless, the positive impacts from the recycling stage must be prorated among the waste management companies and the industries that make use of the VSW. The collection and recovery of waste in its diverse ways serve as suppliers to the recycling industry, as shown in Tirado-Soto and Zamberlan (2013).

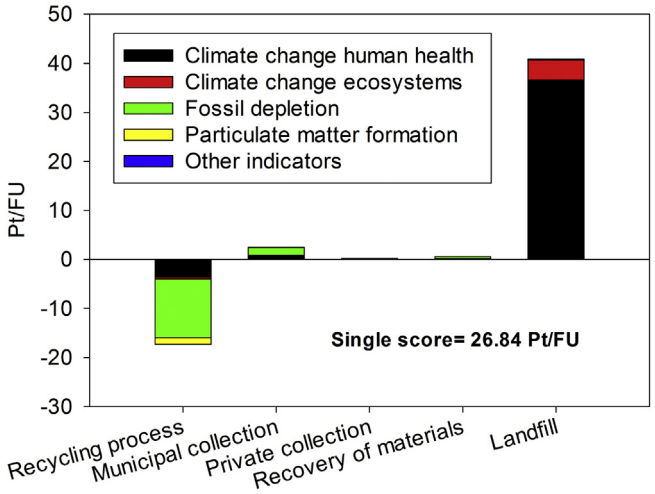

Fig. 4. Environmental impact indicators for the city of Celaya, Guanajuato, MX. Endpoint indicators per functional unit (FU).

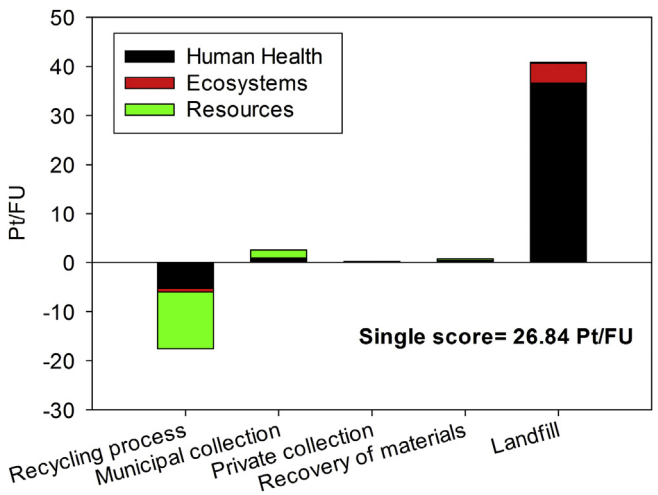

Fig. 5. Environmental impact indicators for the City of Celaya, Guanajuato, MX. Endpoint indicators per functional unit (FU).

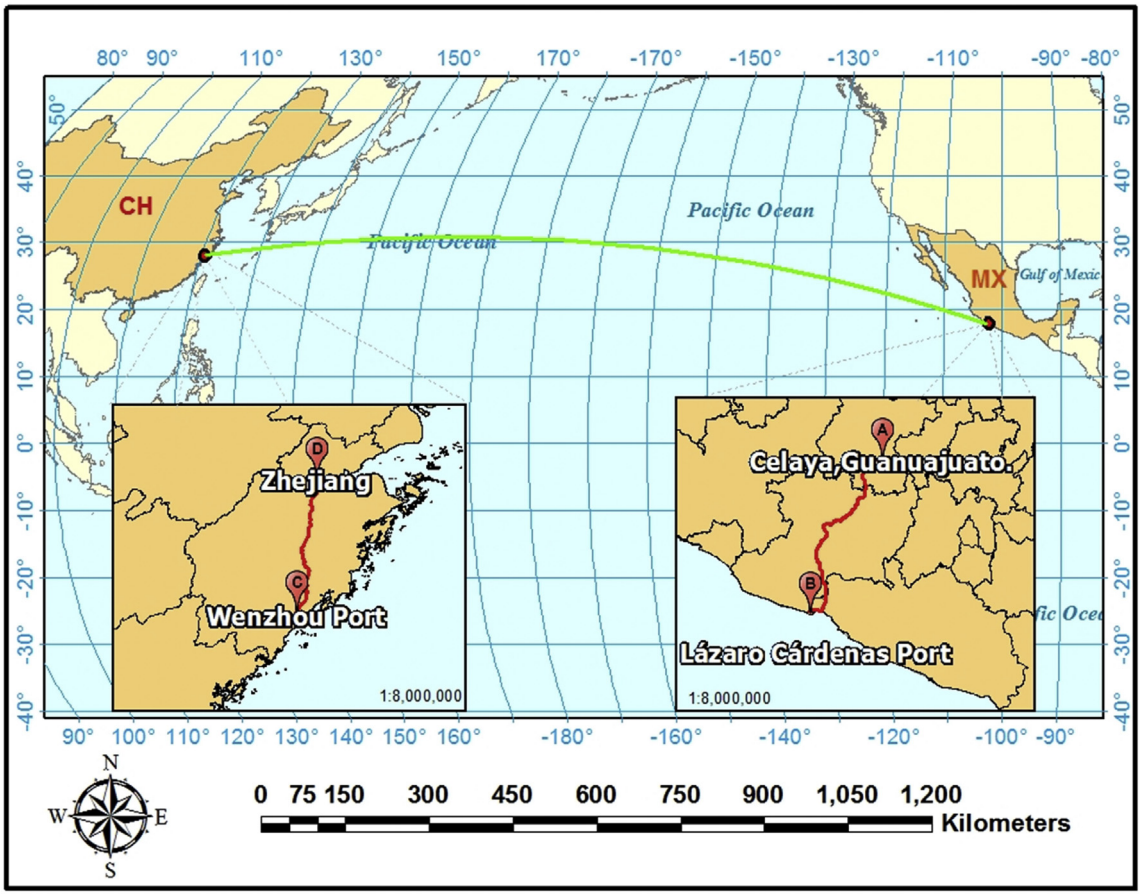

Fig. 6. Route followed to export PET from Guanajuato, MX to Zhejiang, CH.

The ReCiPe's endpoint indicators evaluate the impact in three categories: human health, ecosystems, and natural resources, as shown in Fig. 5. It is worth noting that the impact on human health is a direct consequence of the climate change associated with emissions from the SL. Due to the fact that these indicators have a global context, they do not consider the direct and immediate impact to vulnerable groups (English et al., 2009). Thus, the need to develop alternatives that allow the evaluation of the direct impact on the different groups, such as waste pickers.

3.3. Environmental impacts of an international recycler scenario

Mexico sells abroad its VSW, mainly to China and the United States, due to the fact that there is a lack of infrastructure in the country to recycle most of the VSW recovered (ECOCE, 2017). China is the major buyer of recycled plastic, with a 56% share of the world market. Thus, Mexico is one in a long list of countries that export recovered plastics to China, mainly PET (Velis, 2014).

In this work, a scenario considering the sales of PET to China was assessed. The frontiers of the system depicted in Fig. 1 were extended to include the site where the recycling of PET takes place. The route followed to transport PET from the City of Celaya, in the state of Guanajuato, Mexico, to the city of Hangzhou, in the province of Zhejiang, China, is shown in Fig. 6. The distance needed to ship PET to China was evaluated through the geographic tool Google Maps. The yields and types of fuel used to transport it by land and sea, as well as the emissions due to the combustion of fossil fuels, were determined through the GREET model (GREET, 2016). A heavy heavy-duty truck with a capacity of 96 m^3, a cargo ship with a capacity of 8500 TEU (1 TEU, twenty-foot equivalent unit, is approximately 33 m^3), and a density of a bale of PET of 220 kg/m^3 were considered.

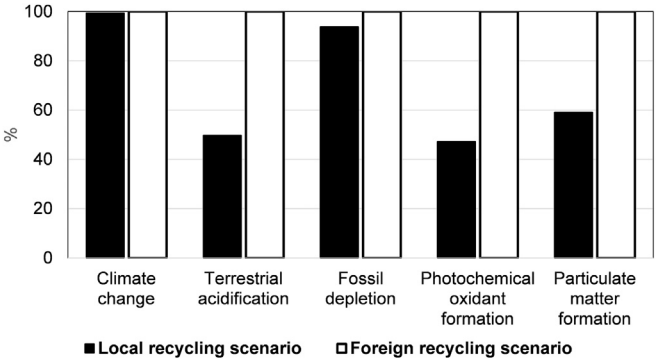

Fig. 7. Comparison of ReCiPe midpoint 2008 environmental impact indicators for the local recycling scenario and the scenario including sales to China.

Under this scenario, 0.44 t of PET/FU are ship to China. The route encompasses 486 mi by road and 7217 nmi by sea; these are reflected in an additional expense of 0.626 L of diesel and 1.722 L of fuel oil per FU. Evidently, this additional use of fossil fuels reduces the positive impacts of recycling. The comparison of the base scenario with the scenario that considers the sales of PET to China is shown in Fig. 7. The values of the environmental indicators for the latter scenario show an increment with respect to the former one. The terrestrial acidification indicator is 50% higher for the China

Table 6
Results of the marginalization index and the survey of waste pickers.

Exclusion forms →	% Illiterate population older than 15+	% Population older than 15 + that finished elementary school	% Private homes with no bathroom facilities	% Private homes with no electricity	% Private homes with no running water	Average number of inhabitants per room in private homes.	% Private homes with dirt floor	% Private homes with no refrigerator	Marginalization Index
Weighting factor	0.8170	0.6012	0.3783	0.3922	0.2025	15.5876	0.4435	0.3941	
Municipal values	3.56	12.56	0.70	0.45	1.79	0.94	3.34	6.11	3.73
Waste pickers values	5.55	8.33	8.33	5.55	8.33	4.11	41.66	11.11	12.93
Age		Gender		Living area		Workday		Previous Work	
Average	47 years	Male	66.67%	Rural	30.56%	8 h (full time)	75.00%	*Waste Picker*	13.89%
Minimum	21	Female	33.33%	Urban	69.44%	4 h (part time)	25.00%	Other	86.11%
Maximum	75								
Economic Income		Healthcare		House owner		Feels discriminated			
1-2 SM[a]	75.00%	None	38.89%	Yes	41.67%	Yes	44.44%		
3-4 SM	25.00%	State provided	61.11%	No	58.33%	No	55.56%		

[a] SM: Minimum Wage equivalent to 4.5 USD per day.

scenario compared with the base scenario, as for the formation of photochemical oxidants' indicator, it is also 50% higher for the second scenario, and the formation of suspended particles is 40% above for the international scenario. Nonetheless, the single score indicator shows that the sales of PET to China don't have a high contribution with respect to the local recycling scenario, since it amounts to a total environmental impact of 27.82 Pt/FU.

3.4. Social impact evaluation

The results from the survey and the estimation of the MI for the waste pickers are presented in Table 6. The first two rows showed the eight forms of exclusion and the weighting factors used in the evaluation of the MI. The weights and the range for each marginalization category (Table 7) were determined based on the official census' data for the county of Celaya, according to the 2010 national census (CONAPO, 2010) The averaged values of the form of exclusion for the county of Celaya and for the waste pickers are also presented in Table 6, showing a great difference in the living conditions of the general population and the waste pickers. The latter group suffers from crowded living quarters and that their houses have dirt floors, which characterizes a deficient construction and unhealthy living conditions. Additionally, the results from the survey show that an important fraction of the waste pickers lives in rural areas, commuting to the city to collect waste, and have at least another low-paying job, e.g. as bricklayers, farm workers, and security guards. It is important to point out, that a high percentage doesn't own a house and has no access to health care. Almost half of the respondents expressed that they feel discriminated by the rest of the society, even though they benefit from their work.

The marginalization categories, as defined by the MI intervals, for the county of Celaya, are shown in Table 7. Additionally, the percentage of population that falls into each category is included (CONAPO, 2010), it can be seen that 73% of the population has a MI of less than 3.86, which place them in the very low marginalization category. The waste pickers, with an MI of 12.93, are in the high marginalization category. Thus, the people that work in the informal collection of VSW live in adverse economical conditions. In Brazil and other countries —as mentioned in Section 1— actions are being taken to formalize their activities by creating a waste pickers' cooperative, as well as establishing laws and regulations that had improved their quality of life (Gutberlet, 2015). The Mexican government has taken no steps so far towards recognizing the role the waste pickers have in the society, in order to improve their quality of life. Favela-Ávila et al. (2013) considered that the waste pickers' living conditions are unfavorable, inhumane, and hostile due to the strong stigma associated with their activities and the social discrimination that they suffer.

This study shows that despite the fact that the collection and storage of valuable waste are mainly done informally, they have a highly positive environmental benefit. An increase of recycling efforts shows potential to reduce adverse environmental impacts. A LCA study done by Song et al. (2013) using the Eco-indicator 99, showed that an increment of 20% in the recycling rate reduced by

Table 7
Waste pickers and city dwellers marginalization index.

Marginalization category	Average index	% of population
Very low	0.00–3.75	73.26
Low	3.76–6.14	4.96
Medium	6.15–8.16	9.08
High	8.17–18.60	12.59
Very High	18.61-or major	0.08
Waste pickers	12.93	

80% the environmental impact of the MSWM. Nevertheless, recycling based on an informal collection of VSW cannot be considered as a cleaner production, since the first step in the recycle chain involves workers in unfavorable conditions. This unfavorable environment doesn't allow them to have a good quality of life.

4. Conclusions

In this work, it was found that the informal recycling of VSW has the potential of attenuating the climate change index by 10% for all the MSWM system, which is equivalent to a reduction of 116.5 kg of CO_2 eq/t MSW. This positive impact could be increased by more efficient collection and recovery strategies. In developing countries, the recovery of VSW is mainly done through informal collection of the waste by waste pickers. This study shows that this informal collection represents 71.69% of the VSW recovery. However, the evaluation of the socioeconomic condition of the waste pickers shows that they suffer from high marginalization in several aspects of their lives, such as education, housing, and access to general goods. In fact, their living conditions are 87% less favorable than for the rest of the population considered. Another relevant aspect is that 89% of the waste pickers manifest that the community doesn't value their job. Under all these circumstances, the VSW's recycling system isn't properly recognized as cleaner production. In order for a clean production to be successful and sustainable, all the people involved in the different levels of the MSWM system must be actively involved in the process, informed of the clean production strategies, and aware of their role in the implementation of the strategies. In this sense, the commercialization and recycling companies along with the governmental institutions should make an effort to improve the waste pickers' quality of life, and put forward strategies for their formal inclusion into the MSWM system.

The information about the informal collection of waste is scarce and hard to obtain, since the waste pickers are spread all over the urban areas, and their routes and meeting points are not well known. Additionally, they are reluctant to participate in a survey and provide any information. It is only by a joint endeavor carried out by researchers, government officials, and the formal companies that commercialize and recycle VSW, that the information on this field can be expanded, and solutions to the waste pickers' high marginalization problem can be generated and implemented.

Acknowledgements

We want to thank the Government of Celaya (2012–2015), Municipal Services Office, and the Municipal Institute of Ecology, for the information provided for the development of this project. As well as the financing projects: Tecnologico Nacional de Mexico, project: 5727.16 and Consejo Nacional de Ciencia y Tecnología, project: CB-2015-254294.

FBS.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.02.065.

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